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FACTORS EFFECTING THE DESIGN OF A SYSTEM FOR TOWING A BODY ON A LONG LENGTH OF WIRE

by

G. W. H. Stevens

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SUMMARY

This note sets forth a method of calculating the diameter of wire to be used and the drag area of target to be towed in order to meet a given requirement of maximum speed of towing and maximum length of tow.

Particular reference is made to a towed target system of the Del Mar Company of Los Angeles U.S.A. and further analysis is made of U.S. Air Force test data on this system.

The test data, despite not having been obtained in a fully controlled scientific experiment, is the best so far known for evaluating the skin drag coefficients of piano wire and predicts a variation both with air speed and with wire diameter.

Analysis predicts that there is a region at high subsonic airspeed and at medium altitudes where the towed system can become unstable.

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1 INTRODUCTION

The U.K. Services have become interested in a U.S. system of towing a target on a long length of piano wire, the Del Mar system. The Army have stated that they would like to be able to tow a target on 15,000 ft of wire at speeds of 400 knots and at heights between 500 ft and 7000 ft. The Navy have stated that they would like to tow as long a length as possible at operating altitudes between 30,000 and 40,000 ft and at speeds not much less than the normal operating speeds at these altitudes.

The purpose of this note is to review the design requirements of a system for towing a body at some distance behind an aircraft and to state certain physical limitations.

2 THE DEL MAR SYSTEM

The Del Mar system is fully described[1] in brochures of the firm but it is essentially a low-drag bomb-like body, which rotates axially in flight and which is towed on a long length of piano wire. This wire can be winched in and out and the target can be released from and retracted into a carrier on the wing. More than one design of target is available and over 30,000 ft of wire can be carried on the drum. The diameters of wire used have been 0.045 in. and 0.051 in.

Test information[2] shows that the system can be operated on lengths of tow up to 30,000 ft, at speeds up to Mach 0.75 and at heights up to 40,000 ft.

3 BASIC DESIGN CRITERIA

There appear to be three basic design criteria which can define a system.

1 The minimum drag of towed body.

2 The worst operating conditions for skin friction.

3 The factor of reserve strength on the wire.

What is required is a logical means of proceeding from them to a design.

3.1 The minimum drag of towed body

The minimum drag of the towed body can be determined on the assumption that the wire near the body can be prevented from whipping. The tension in the wire, arising from the combined weight and drag of the body, must be sufficient that transverse waves in the wire will travel faster than the airflow[4]. This is a condition which can be used to determine the diameter of wire to satisfy the requirement of a maximum towing length and maximum speed, subject to the maximum stress limitation in the wire being stated. This design relationship is worked out in Appendix 1.

It is seen that for a given speed the length of tow is proportional to the diameter of the wire and it also depends directly on the skin drag coefficient of the wire. It is also seen that the maximum towing speed is related to the tenacity, e.g. strength/weight ratio, of the wire and, for high speed towing, a high quality wire is required. There is a critical speed above which it would be impracticable to tow a body stably even on a short length of tow. These critical speeds are calculated to occur in the low supersonic range by the method of Appendix 1, assuming that if this can be applied at such speeds, the high density of steel wire is an advantage and it would not be possible to obtain as good a performance with a low density plastic filament such as nylon or polypropylene.

3.2 The skin drag of wire

It appears that the best data on the skin drag of piano wire can be deduced from actual air tests on a Del Mar system[2]. Early wind tunnel experiments on the drag of wires[7] do not give such reliable results on skin drag although the estimates of normal profile drag appear to agree closely with the more recent results.

The drag measurements on the Del Mar system are analysed in Appendix 2. The values of skin drag coefficients show a variation with speed and wire diameter ranging from about 0.018 to 0.012 over the speed range of 175 to 300 knots. The value quoted by Hoerne, and used by the Del Mar Company in their design brochure, lies within the observed range. The trend of variation with speed and diameter agrees with that predicted by the method of Glauert and Lighthill[9] despite the fact that the method does not give the correct absolute magnitude.

It is presumed that the wire used in the tests at Eglin Air Force Base, U.S.A. was substantially new, smooth and oiled. It is of some concern whether the skin friction increases as the surface deteriorates. The possibility of drums of wire used at sea on aircraft carriers being effected by sea spray must not be overlooked and some factor in design to meet this contingency may be required.

3.3 Maximum working stress

The Del Mar Company claim, the report of Eglin Air Force Base, concurs, that it is possible to work to 85% of the ultimate strength of the wire. It is difficult to believe that the straining due to winding on a limited diameter of drum, disturbances due to uneven flight and non-uniform airflow along the length of the wire and effects of winch operation do not make it necessary to have a greater factor of safety. The standard deviation of the tensions measured in different flights for the same operating conditions is 7½% of the mean. Most of this observed variation arises from the second cause mentioned above and any high frequency fluctuation will be averaged out in the test readings. With this observed standard deviation of tension it is clearly not safe to work to such a low factor for it would give a one in twenty chance of failure.

The major source of weakness in the system arises from the fact that the wire is wound onto a drum of limited diameter. A wire of diameter 0.045 in. wound on a drum of 9 in. diameter will have a difference of strain between the axis and the skin of 0.005. This is of the order of the yield strain of well-drawn piano wire. Since, in this equipment, there are no tension blocks and surge drums, as in a balloon winch, the tension is transmitted directly to the winch. Thus the elastic limit of the wire is likely to be exceeded on the drum and the wire to be given a permanent set. When the wire is unwound again its natural coil will be straightened and the wire will be unevenly stressed across its section. It will not necessarily be rewound with the coils in the same lay.

To operate on a winch as described above it is necessary to use a sufficiently soft wire so that it yields to the winching strains. However, the process of winching in and out at a high stress will work harder the wire and it is likely to attain eventually a brittle condition.

The yield strain for many qualities of piano wire is in the region of 0.007 to 0.009 and the ultimate strain is about 0.012 and 0.015. It would appear desirable to limit the local strain to 0.010 which would require the mean working strain not to exceed 0.005 if, in fact, a local variation of ±0.005 occurs on the winch. This would limit the stress to about 60-70 tons per sq in. in the wire.

In the recorded test data[2] the highest tension recorded, 354 lb, is 72% of the quoted ultimate, 490 lb, and represents a mean stress of nearly 100 tons per sq in. so that the wire will be suffering permanent strain.

In addition to the effects discussed above there will be tension surges of which little is known of their significance. It is likely that any high frequency drag variation due to eddy shedding by the towed body may be damped down by the time the effects arrive at the towing point because transient motions are heavily damped at low speeds.

4 DESIGN FOR A LOW ALTITUDE - HIGH SPEED SYSTEM

The U.K. Army have asked if it is possible to design a system for ground-to-air firing in which a target is towed on a 15,000 ft length of wire at 400 knots. The heights of operation would be from 500 ft to 7000 ft. The diameter of wire necessary for this system can be calculated from equation (14) of Appendix 1 and the drag area of the target from equation (12). The following data are relevant.

Skin drag coefficient of the wire at 400 knots	C_s	=	0.012
Length of wire	L	=	15,000 ft
Density of air at 7000 ft	ρ_H	=	0.00190 Slugs per cubic ft
Maximum speed	V	=	400 knots
Maximum working stress	aS	=	60 tons per sq in.
Density of wire	Δ	=	15 slugs per cubic ft

It is then calculated that the diameter of wire should be 0.093 in. which is hardly practicable as a single wire. However, if the stress level wire increased to 120 tons per sq in., which the APGC report claims can be realised, the diameter of the wire could be reduced to 0.037 in. which is compatible with the present Del Mar system.

The drag area of the target should be 0.74 sq ft for the 0.093 in. wire and 0.075 sq ft for a 0.037 in. wire. If, however, a wire of 0.045 in. diameter is accepted the drag area of the target should be 0.115 sq ft. These estimates of minimum drag area have not taken into account the weight of the target which would permit a slight further reduction of the drag area before the target became unstable.

5 THE PERFORMANCE OF THE DEL MAR SYSTEM WITH DF-4MFC TARGET

The performance of this particular system of the Del Mar Company will be assessed on the basis of the design theory of this memorandum. The target for this system weighs 46.5 lb and has a drag area of 0.151 sq ft below M = 0.9. This drag area has been evaluated from a profile of 1.675 sq ft and a C_{DO} of 0.085 quoted in the Company's brochure, a small fixed allowance being made for the induced drag.

At Fig.1 is reproduced a curve showing maximum towing length against indicated airspeed in knots using the U.S. factors for maximum working tension. Curve (b) gives the relationship based on the new estimates of skin drag coefficient and Curve (a) gives the original relationship from the company's brochure which used a constant coefficient of 0.015. It is seen that the system does not quite meet the U.K. Army requirement as the target is too big.

It is useful to see how target weight and drag, wire weight, and wire drag contribute to the total tension and this is illustrated in Fig.2. Wire drag accounts for about 80% of the total tension and wire weight is negligible at the order of airspeed at which it is required to fly. The basis for calculated these curves is summarised in Table 2.

6 HIGH SPEED - HIGH ALTITUDE INSTABILITY

Although the drag of the DF-4MFC target is sufficient to ensure stability of the end at low altitudes it is shown in Appendix 1 that, if the system is flown at certain heights and speeds, the end of the wire and target can become unstable. This is a phenomenon which can occur with parachute strops[3].

Stability is assured when

$$K_o \sigma \sec^3 \alpha > m$$

where m is the mass per unit length of the wire

K_o is the velocity coefficient of drag at normal pressure

σ is the density ratio ρ_H/ρ_o

α is the inclination of the wire from the horizontal at the target.

This inequality can be upset by flying higher and so reducing σ or by flying faster and so reducing α. However, as sonic speeds are approached K_o will increase and restore the inequality. According to the firm, K_o will begin to rise sharply at $M = 0.9$.

The value of K_o is 1.81×10^{-4} and the ratio m/K_o is worked out for the following diameter, d, of wire

d in.	m slugs per ft	m/K_o
0.040	1.295×10^{-4}	0.715
0.045	1.685	0.93
0.051	2.12	1.175

The finite weight of target is clearly important in limiting the instability to high subsonic speeds and the envelop is plotted in Fig.3 for height against true speed for the cases of 0.045 in. and 0.051 in. wires. The high Mach number boundary of the envelop is only approximate. It is taken arbitrarily at $M = 0.9$ as no exact information is available on the drag rise.

The plots show that the extreme tests of APGC report are still in the stable region of flight but approach the calculated envelop very closely for the 0.051 in. wire. They illustrate that increasing the strength of the wire may be no answer to improving the performance without reviewing the system as a whole.

7 LIMITS OF LENGTH OF WIRE WHIP

If the density ratio, σ, is below the value that satisfies the critical condition for stability, waves will be built up in the wire over a distance where the skin drag does not compensate for the inadequate target drag. Thus if the target drag is deficit by $K\ V^2\ \delta\sigma$ then, beyond a point where the skin drag compensates for the loss, the waves in the wire will be positively damped.

This length, δL, can be expressed in terms of $\delta\sigma$

$$\delta L = \frac{C_1 A}{C_s d}\,\delta\sigma$$

This coefficient for $\delta\sigma$ depends on the diameter of the wire and has values of approximately 2650 and 2350 for 0.045 in. and 0.051 in. wire diameters respectively.

Since σ is a fracture less than unity the length of wire which will whip will always be well less than the above numerical values. In the cases that have been illustrated only a few hundred feet could whip in the worst case.

In view of the low reserve factor of strength in existence systems when towed at speeds approaching the instability region it is doubtful if any whipping would actually be observed. It is expected that the wire would break before any effects are noticeably seen or felt.

8 CONCLUSIONS

It is predicted that the present Del Mar system can be unstable in certain high speed - high altitude regions. It is important that a system be designed so that this unstability does not encroach into operational flight envelopes.

It is important to design a system as a whole, matching the target weight and drag to the size of cable used. An objective design procedure is given.

The test data of Air Proving Ground Centre, Eglin Air Force Base, U.S.A. has been further analysed to give better estimates of skin drag coefficient of piano wire. The coefficient ranges from 0.019 to 0.012, decreasing with speed over the range 175 knots to 300 knots and are expressed in terms of the profile area per unit length (e.g. wire diameter).

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4	Phillips, W.H.	A theoretical analysis of the oscillations of a towed cable. N.A.C.A. Report No. 1796.
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ATTACHED:-

Appendix 1 & 2
Tables 1 & 2
Fig. No. 1-5 SME 85593/R-SME 85596/R
Detachable Abstract Cards

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APPENDIX 1

METHOD OF DETERMINING THE DIAMETER OF WIRE FOR A LONG TOW LENGTH

The maximum force in a towed system occurs near the aircraft and, in a long tow length, most of it arises from the skin drag in the wire. The weight of the wire and the weight and drag of the towed body are also contributions to the force but much of the weight of the wire is supported by airlift on the cable. In order to achieve a longer length of tow, or a higher speed of tow, it is necessary to increase the diameter of the wire but this, in turn, increases the drag per unit length.

The configuration of a towed wire has been worked out by many people, originally by Glauert,[5,6] and it is clear from this work that the wire will be substantially straight over most of its length. The slope of the wire tends to an assymptotic value, θ, determined by the equilibrium of lift and weight on a unit length of wire but it will vary near the target because the slope, α, at the target is determined by the resultant of drag, weight and lift on the target.

2 CRITERIA FOR MINIMUM DRAG OF TOWED BODY

Clearly, an approach to the problem of designing an efficient system for towing a long length of wire is to find criteria for the lowest drag of body that can be towed satisfactorily. If the drag is too low it is possible to induce transverse whipping in the wire. This instability should be avoided because it will be associated with tension surges and a larger factor of safety on the wire strength is required.

It has been shown[4], and there is some experimental evidence[3], that the drag of the body must be sufficient to ensure that transverse waves in the wire will travel faster than the airflow tangential to the wire and these waves travel slowest near the target where the tension is least. If the wire is increased in diameter and is thereby heavier, the tension in the wire must be increased to maintain the wave velocity. The following simple condition for stability in the wire near the towed body holds

$$\sqrt{\frac{T}{m}} > V \cos\alpha \qquad (1)$$

where T is the tension in the wire

m is the mass per unit length of the wire

V is the speed of airflow

α is the angle of the airflow at the target.

The tension T is least near the target so that if the condition

$$\sqrt{\frac{T_o}{m}} = V \cos\alpha \qquad (2)$$

is satisfied at the target the wire will be stable along the whole of its length.

The tension, T_o, is the resultant of weight, W, and the drag, D, of the target so it is possible to write

$$T_o = (W^2 + D^2)^{\frac{1}{2}} > mV^2 \cos^2 \alpha \qquad (3)$$

for the conditions of stability. Moreover, $\tan \alpha = \frac{W}{D}$, so that

$$(W^2 + D^2)^{3/2} > mV^2 D^2 \qquad (4)$$

When a drag force proportional to the square of the velocity can be assumed it is possible to write $D = KV^2$ whereupon

$$\sec^3 \alpha > \frac{m}{K} \qquad (5)$$

The coefficient K will depend on air density so that it is possible to write

$$\sec^3 \alpha > \frac{m}{\sigma K_o} \qquad (6)$$

where K_o is the coefficient at sea level and σ is the density ratio.

When the speed of towing is high sec α will not be very different from unity. Thus it is seen that if K_o is equal to m/σ at the height for which the system is to be operated then stability is always assured. It is also seen that when the weight of the wire is increased the drag coefficient must be increased proportionally. If K_o is less than the value given by m/σ then the system may still be stable at some lower speed because of the angle α that the wire is inclined to the airflow at the towed body.

3 TENSION IN THE CABLE

In a very long length of towed wire, apart from the curved portion near the target, the inclination with respect to the airflow, assuming it to be homogeneous over the whole length, is substantially constant. It can be shown that the angle of inclination, of the wire to the airflow, approaches an assymptotic value, θ, and, for small angles,

$$\theta = \sqrt{\frac{mg}{k}} \times \frac{1}{V} \qquad (7)$$

The quantity, k, is the normal drag area multiplied by half the air density. It is seen that the angle, θ, is inversely proportional to the airspeed, V.

The rate of change of tension with length along the wire at this slope, θ, is

$$\frac{dT}{ds} = k_s V^2 \cos^2 \theta + gm \sec \theta \qquad (8)$$

but as θ is a small angle it is adequate to many cases to write

$$\frac{dT}{ds} = k_s V^2 \qquad (9)$$

where k_s is the velocity coefficient for skin drag. Thus in the high speed case the tension T_a at the aircraft approximates to

$$T_a = k_s V^2 L + T_o \tag{10}$$

where L is the length of the wire. The curvature of the cable near the towed body and the sag of the cable will produce a small increment of tension.

The tension, T_a, can be expressed also in the following form

$$T_a = \tfrac{1}{2}\rho_H (C_D A + C_s d\, L) V^2 \tag{11}$$

where ρ_H is the air density appropriate to the design height

d is the diameter of the wire

L is the length of the wire

V is the airspeed in ft per second

C_s is the skin drag coefficient as defined in R & M 307 = $2k_s/\rho_H d$

$C_D A$ is drag area of towed body

This is a convenient form for applying the criteria of section 2.

4 RELATIONS FOR CRITICAL TERMINAL CONDITIONS

Co-relating the forms of expression in section 2 and 3 the condition $K = m$ when α tends to zero can be replaced by

$$\tfrac{1}{2}\rho_H C_D A = \frac{\pi}{4} d^2 \Delta \tag{12}$$

where Δ is the density of the wire.

The maximum tension will also be limited by the diameter of the wire and the tension can be expressed in terms of the ultimate strength, S, of the wire by

$$T_a = a \times \frac{\pi}{4} d^2 S$$

where a is a factor for safe working below the ultimate strength.

A substitution can now be made in equation (11) giving

$$a \frac{\pi}{4} d^2 S = \left(\frac{\pi}{4} d^2 \Delta + \tfrac{1}{2}\rho_H C_s d\, L\right) V^2 \tag{13}$$

which can be simplified to

$$d = \frac{2\rho_H C_s L}{\pi\left(\frac{aS}{V^2} - \Delta\right)} \tag{14}$$

which gives the minimum wire diameter.

5 WIRE DIAMETER TO MEET A REQUIREMENT

In equation (14) there has been obtained an explicit equation for the minimum diameter of wire to satisfy a specified requirement of maximum speed and length of tow. It is seen from this equation that the efficiency of meeting a particular requirement is dependent upon a high tenacity, defined as S/Δ, and it is important that $aS/\Delta V^2$ is substantially larger than unity. If this quantity is not very different from unity then the diameter of wire for a modest length of tow becomes prohibitive. This is a condition that is approached if the design speed is high. This is a physical limitation noted with respect to the design of strops for parachute equipment at high speeds[3].

It is also noted from equation (14) that d/L is a function of the densities of the air and of the wire material. It is also important to note that the ratio S/Δ represents the tenacity of the material and this quantity has about the same magnitude for both steel and nylon wires. For materials of the same tenacity it is possible to say that the ratio d/L is proportional to the ratio of the densities ρ_H/Δ. Thus if a low density material such as nylon or polypropylene wire is used, the diameter of the wire must be seven to eight times the diameter of piano wire to meet the same requirement of maximum length of tow. Since tensions will be roughly proportional to the diameter of the wire, the system with the higher density wire is clearly the more efficient.

6 CORRECTION TO TENSION FOR WEIGHT OF WIRE

The tension in the wire will partly arise from its weight and the rule of Glauert[5] can be used which states that the increase in tension due to weight is given by the vertical depression of the target below the wire. This allows also for the curved portion of the towing wire near to the target.

Having determined the wire diameter on the basis of the first order equation (14) one should re-evaluate the wire tension allowing for the component of weight of the wire and for the exact terminal tension. From equation (7) an expression for the weight component can be introduced as a second order term in equation (10) to give

$$T_a = T_o + k_s V^2 L + \sqrt{\frac{mg}{k}}\,\frac{L}{V} \times mg \qquad (15)$$

The above equation can be expressed as

$$T_a = T_o + k_s V^2 L \left(1 + \left(\frac{mg}{k}\right)^{3/2} \times \frac{k}{k_s}\,\frac{1}{V}\right) \qquad (16)$$

in which it is seen that contributions from the weight of the wire can be expressed as a correction factor to the skin drag coefficient.

The coefficient of L is of the form $V^2 + (A/V)$ which has a minimum value at a certain value of the airspeed, V. This speed, however, is found to be below practical flying speeds so that the weight of the wire never becomes a term more prominent than the skin drag.

APPENDIX 2

DATA ON DRAG OF WIRES

For many years now the basic data on the drag of wires are those established in the 1914-18 period[7] and obtained at quite low airspeeds. Although these probably provide good estimates of the coefficient for normal airflow they do not directly give reliable estimates for tangential flow.

There has been dearth of reliable data for determining the aerodynamic forces on a towed cable whose inclination to the direction of airflow is only a few degrees. It is considered that the proving trials data contained in a proving test report on a U.S. B57 installation of the Del Mar system[2] are the best known to us.

2 DATA FROM LOWSPEED WIND TUNNEL

In the original work[7] the drag of lengths of wire and stranded cable were measured at various angles to the airflow, both normally and tangentially, but the scatter of the data and the relatively small measured quantities at or near tangential flow did not permit very accurate estimates of skin friction to be obtained. The measurements established[10] that the drag coefficient could be related to the normal component of the airflow, that is the drag per unit length is equal to $\frac{1}{2}\rho d\ C_n\ V^2 \sin^2 \alpha$ where α is the angle that the airflow makes to the wire. It is believed that this rule holds when α is only a few degrees.

Related to the profile area the normal drag coefficients obtained from this data are 1.13 for a smooth wire and 1.02 for a cable. However, there can be some ambiguity in measuring the diameter of a cable and in this case it was based on cable circumference. The corresponding estimates for the flow tangential to the cable, still related to the profile area, are 0.027 for a smooth wire and 0.040 for a cable. If the coefficients are expressed in terms of unit surface area then the above figures should be divided by π.

The estimate of 0.027 for a smooth wire is high compared with the value of 0.015 quoted by Hoerne[8].

3 DATA FROM FLIGHT TRIALS

Some extensive measurements of drag of a Del Mar piano wire target system are given in APGC Report TR-59-39[2] from U.S.A.F.B. Eglin Field. This report gives the drag of a target system at six different towing speeds and with five different lengths of tow up to 20,000 ft. The data are given for two diameters of wire, 0.045 in. and 0.051 in. The measurements are represented in a re-arranged form in Table 1.

This report was passed to the Aerodynamics Department at R.A.E. for comment and analysis. As far as they could judge, the data was the best that they had seen on the subject and, from them, it was possible to deduce the skin drag coefficients of the wire from the rate of change of wire tension with length. Therefore, tension difference are also included in Table 1.

Although the data show the proper trends there are obviously one or two grossly erratic readings which do not fit. For the calculations made in this memorandum the figures must be accepted without knowledge of the standard deviations of the method of measurement despite the fact that the method of measuring the vertical height separation must be subject to errors as significant as some of the separations measured.

By comparing the tensions measured at the same conditions on different flights an estimate of standard deviation of tension can be obtained. This has been done for lengths of tow 10,000 ft and greater and a figure of $\pm 7\frac{1}{2}\%$ is obtained. Within this observation it is rather surprising that the test report concludes that it is safe to work to 85% of the ultimate breaking strength of the wire.

4 THE MEAN INCLINATION OF THE WIRE

Although the target may cause the wire to be curved downwards near the target the ratio of the target/aircraft height separation to the length of wire will give a good estimate of the slope of the wire. In Fig.4, there are drawn the two calculated curves using the normal drag coefficient of 1.13. Estimates of inclination from the figures of Table 1 and are given for the 0.045 in. wire for three airspeeds. These estimates scatter about the calculated curves to give satisfactory agreement within the limitations of the method of test. The calculated inclination of the cable will be used to correct the tension differences of Table 1 using equation (16) of Appendix 1.

5 THE MEAN SKIN DRAG COEFFICIENT

The mean skin drag coefficients for the different diameters of wire and for the various speeds have been worked out and plotted in Fig.5. Some variation of coefficient with both speed and wire diameter is indicated, decreasing with increasing speed and increasing wire diameter. The value quoted by Hoerne[8] is confirmed to occur at speeds about 200 knots or slightly higher. It is fortunate that the trend of variation is such as to give some relief as wire diameter and speeds are increased in attempting to meet a given requirement.

With regard to the trend of variation of skin drag with speed, the method of Glauert and Lighthill has been used to estimate the drag of very long lengths of wire. The method confirms the trends in relative values both with respect to speed and to change in wire diameter but, unfortunately, it gives numerical values too low by a factor of forty.

The simple design theory of Appendix 1 assumes a skin drag coefficient independent of speed and wire diameter and a drag proportional to the square of the speed. It still appears possible to use this simple theory provided a skin drag coefficient appropriate to the maximum design speed is used. In the case of subsonic speeds greater than the 300 knots of the present data any further reduction in the coefficient will be slight and the value of 300 knots could be used.

TABLE 1

ABSTRACT OF DATA FROM U.S.A. REPORT APGC-TR-59-39

Indicated air speed knots	Tow length ft	0.045 in. wire diameter						0.051 in. wire diameter					
		1st Test			2nd Test			1st Test			2nd Test		
		Tension lb	Tension diff lb	Depression of target ft	Tension lb	Tension diff lb	Depression of target ft	Tension lb	Tension diff lb	Depression of target ft	Tension lb	Tension diff lb	Depression of target ft
300	1,000	63		300	60		50	65		60	87		300
	5,000	123	60	560	118	58	320	127	62	200	150	63	450
	10,000	196	73	-	192	74	640	198	71	520	225	75	750
	15,000	229	33	1,000	259	67	800	277	79	700	305	80	900
	20,000	354	135	1,000	337	78	995	354	77	1,000	375	70	1,300
275	1,000	53		240	52		90	56		80	71		200
	5,000	102	49	500	103	51	375	110	54	400	127	56	600
	10,000	164	62	-	159	56	650	176	66	720	194	67	1,300
	15,000	244	80	1,100	220	61	860	244	68	1,000	254	60	1,100
	20,000	306	62	1,400	280	60	1,050	300	56	1,300	321	67	1,500
250	1,000	47		200	46		100	48		160	60		200
	5,000	87	40	520	88	42	400	96	48	450	111	51	620
	10,000	141	54	-	141	53	740	157	61	790	166	55	940
	15,000	210	69	1,200	192	51	1,040	215	58	1,150	235	69	1,400
	20,000	274	64	1,500	247	55	1,350	270	55	1,440	287	52	1,750

TABLE 1 (CONTD.)

Indicated air speed knots	Tow length ft	0.045 in. wire diameter						0.051 in. wire diameter					
		1st Test			2nd Test			1st Test			2nd Test		
		Tension lb	Tension diff lb	Depression of target ft	Tension lb	Tension diff lb	Depression of target ft	Tension lb	Tension diff lb	Depression of target ft	Tension lb	Tension diff lb	Depression of target ft
225	1,000	43	35	100	39	39	130	43	40	200	52	44	400
	5,000	78	44	480	78	44	430	83	53	500	95	52	760
	10,000	122	60	-	122	51	850	136	56	900	148	60	1,250
	15,000	182	62	1,300	173	47	1,260	192	40	1,300	208	42	1,650
	20,000	244		1,600	220		1,680	232		1,580	250		1,960
200	1,000	36	36	160	32	35	125	34	40	160	43	37	500
	5,000	72	37	500	67	38	510	74	44	540	80	47	800
	10,000	109	62	-	105	43	1,040	118	50	950	127	51	1,350
	15,000	171	30	1,500	148	41	1,360	168	38	1,430	178	42	1,700
	20,000	201		1,700	189		1,640	206		1,850	220		2,150
175	1,000	32	30	120	26	30	145	30	33	200	34	33	544
	5,000	62	30	660	56	36	560	63	42	630	67	42	850
	10,000	92	44	-	92	35	1,160	105	41	1,100	109	41	1,550
	15,000	136	37	1,500	127	37	1,700	146	32	1,550	150	40	1,960
	20,000	173		1,800	164		1,950	178		2,180	190		2,580

TABLE 2

RE-EVALUATION OF DEL MAR PERFORMANCE ESTIMATE USING REVISED WIRE DRAG DATA

Target DF-4MFC

Weight 46.5 lb

Drag area 0.151 sq ft

Wire Music wire 0.045 in. diameter

Weight 5.4×10^{-3} lb per ft

Towing speed knots	Skin drag coeff.	Target drag lb	T_o lb	T_a-T_o lb	F	T_s lb	L thousands ft
160	0.0195	12.8	48.2	367.8	1.11	331	53.3
180	0.0185	16.2	49.2	366.8	1.08	342	45.6
240	0.0145	28.8	54.5	361.5	1.04	348	34.2
300	0.0130	45.0	64.7	351.3	1.024	343	25.6
360	0.0125	64.8	80.0	336	1.017	331	16.4
420	0.0120	88.0	99.3	316.7	1.01	313.5	11.8

T_o = wire tension at target

T_a = maximum wire tension at aircraft

= 416 lb

F = factor total tension/skin drag to correct for component of wire weight

T_s = tension due to skin drag of wire

L = maximum tow length

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FIG.1.

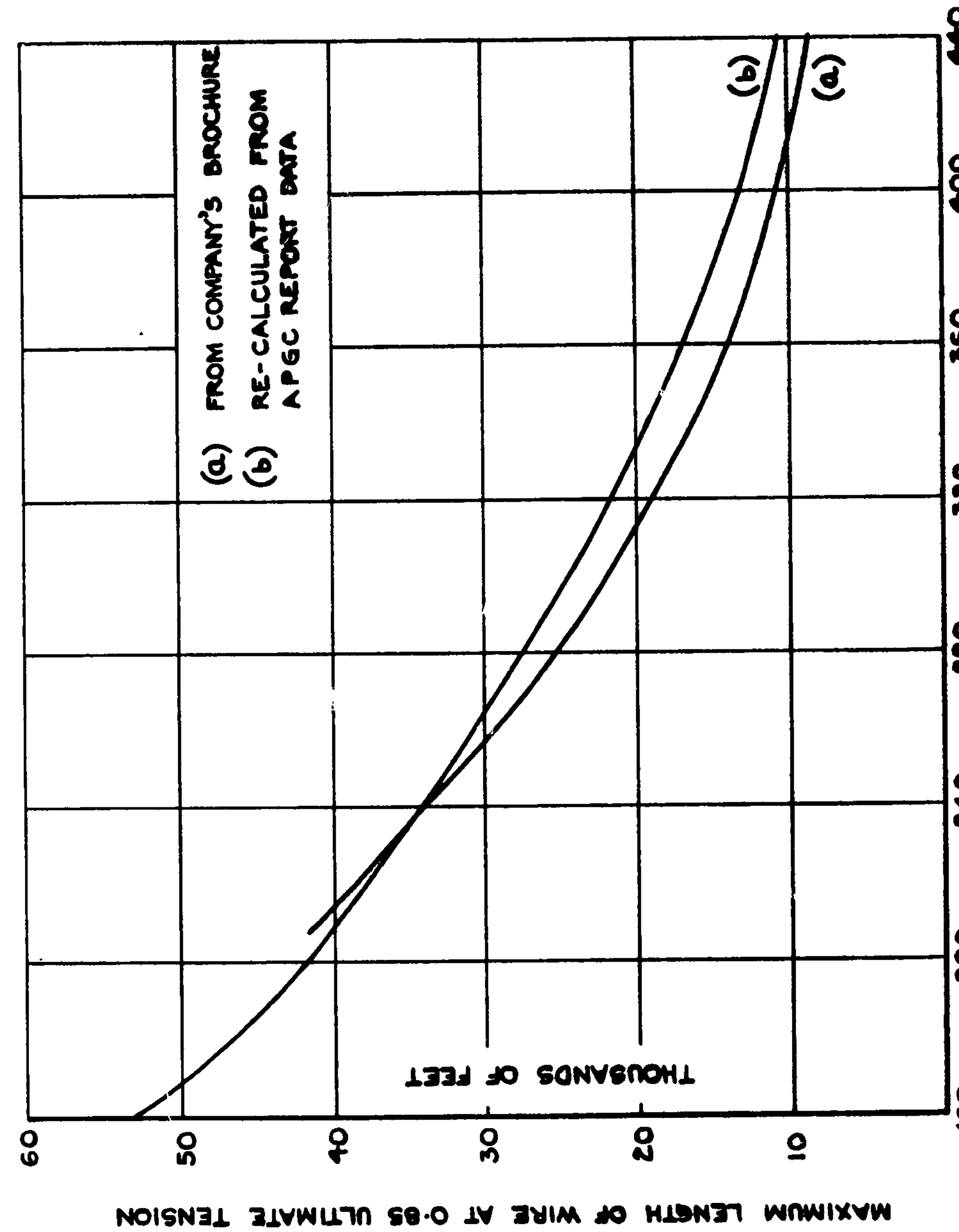


FIG.1. RELATION BETWEEN MAXIMUM TOW LENGTH AND AIRSPEED.

DATA FOR ·045" WIRE.

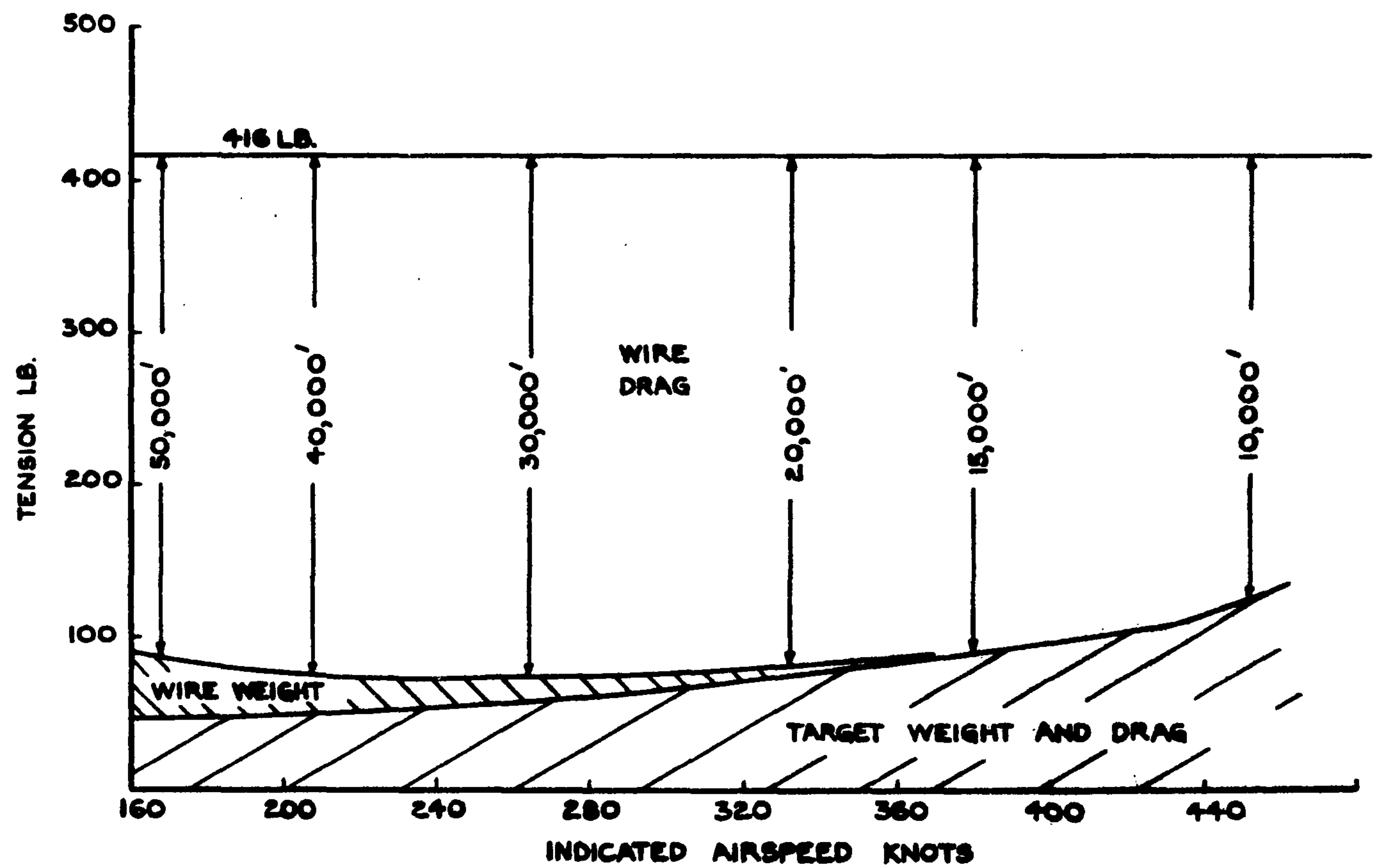
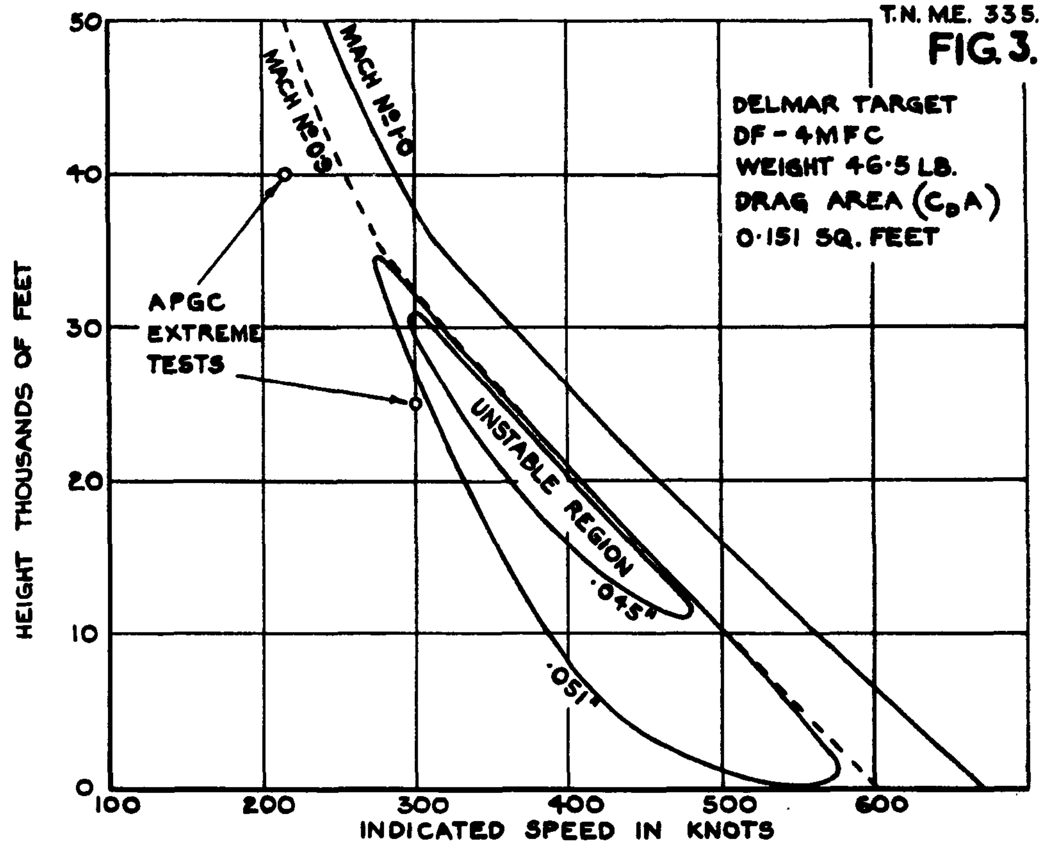


FIG. 2. ANALYSIS OF CONTRIBUTIONS TO TENSION. VARIATION WITH SPEED.

BREAKING STRENGTH OF WIRE 490 LB.



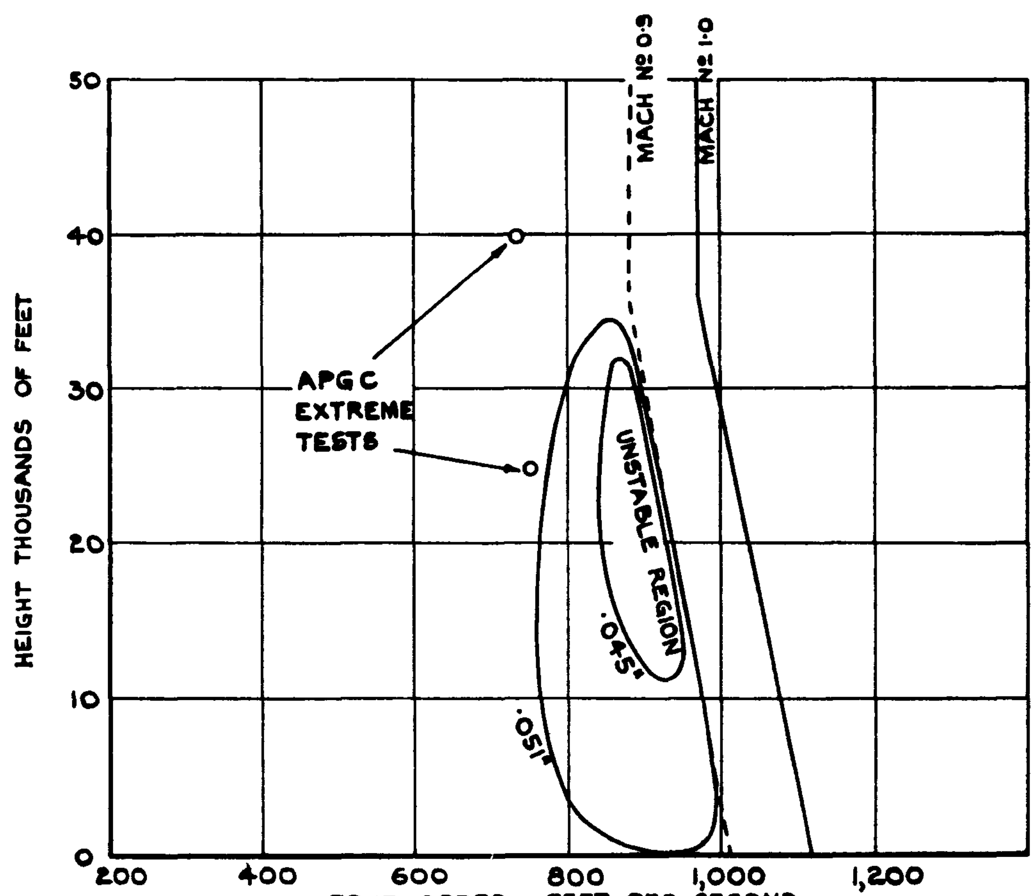


FIG. 3. UNSTABLE FLIGHT REGIONS.
ENVELOPS FOR ·045" AND ·051" DIA. WIRE.

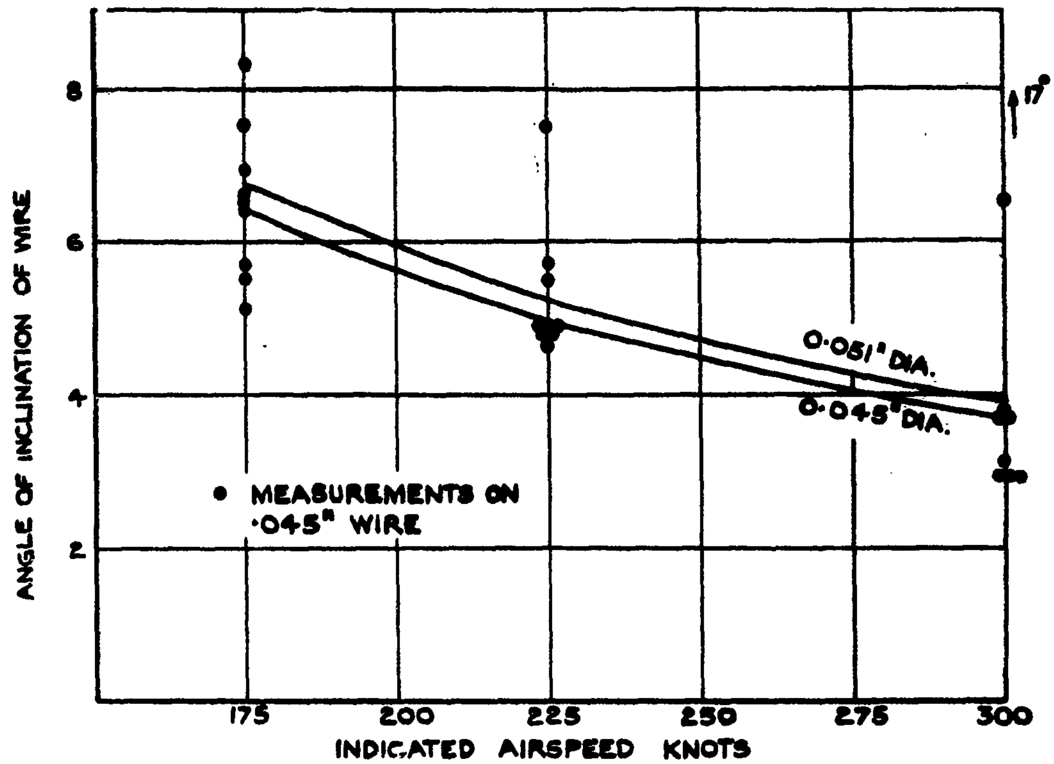


FIG. 4. MEASURED MEAN INCLINATIONS OF WIRE. COMPARISON WITH CALCULATED CURVES.

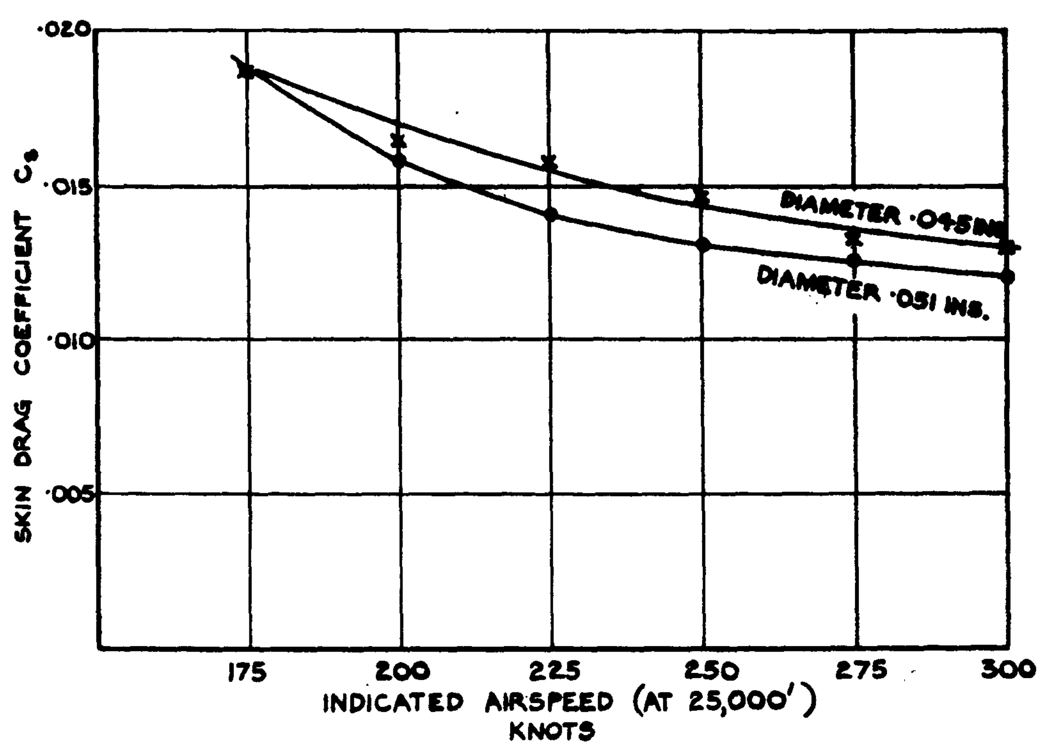


FIG. 5. MEAN SKIN DRAG COEFFICIENT FOR SMOOTH WIRE.

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The test data, despite not having been obtained in a fully controlled scientific experiment, is the best so far known for evaluating the skin drag coefficients of piano wire and predicts a variation both with air speed and with wire diameter.

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